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16. ABSTRACT

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JOURNAL ARTICLE

DETECTION OF CENTRIPETAL HEAT-ISLAND CIRCULATIONS FROM TOWER DATA IN ST. LOUIS

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Abstract. Hourly averaged meteorological data gathered by a 25-tower network about St. Louis during 1976 are used in a search for centripetal circulations generated by the urban heat island. Considering data collected when the network resultant speed was less than 1.5 $m\,s^{-1}$, two data classes of several hundred hours each are formed. One class is associated with weak heat islands, daytime hours, and convective instability, while the other class is associated with strong heat islands, nighttime hours, and extreme rural stability. Mean centripetal flows are clearly discernible from data of both classes, but the convergence is stronger for the flows associated with the weaker heat islands. This unexpected result is explained in terms of the ease with which sustained vertical motions can be generated over the city by the available forcing under different stability regimes. The detectability of the heat-island influence diminishes very rapidly with increasing speed of the large-scale flow.

1. Introduction

The urban heat island, a temperature anomaly resulting from fuel combusion and the contrasting radiation budgets of the urban and rural surfaces, has been described by numerous investigators (e.g., Chandler, 1965). Measurement of temperatures from a surface network of stations is a relatively simple task, and it is not unusual to find that the central urban area is several degrees warmer than the surrounding countryside. Under calm or light wind conditions, it is easily theorized that the urban heat island will generate a centripetal circulation as cool, rural air moves inward and rises over the city in response to thermally-induced pressure gradients. Such flows have been simulated by numerical models (Vukovitch, 1971). However, attempting to obtain direct evidence of centripetal flows in urban regions is an endeavor beset with complications. The large-scale pressure gradients never completely vanish, local terrain and roughness features influence the flow, and land-use variations may spawn local heat islands within the urban complex (Clarke and Peterson, 1973). Despite these difficulties, some observations have been reported which indicate that the heat island circulation may be detectable under proper conditions, although these data have usually been taken over quite limited duration or spatial extent.

Okita (1960), using an ingenious method, deduced the existence of centripetal flows in Asahikawa, Japan by observing that rime ice is formed on the windward side of tree branches when impinged upon by supercooled fog. Such fogs were

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frequently present on winter nights with light winds, and reported observations covered widely separated locations about the city on six nights. Pooler (1963) detected an inward flow from anemometric tower data gathered in Louisville, Kentucky. Examining a six-month record of observations, Pooler found the pattern was most evident for a set of 15 individual hours where the winds were calm as measured from atop a 160-m television tower. The atmospheric conditions existing in 13 of the 15 hours were classified as stable, and influence of drainage winds from moderate slopes was also apparent. Chandler (1965) described investigations in London where speed and direction of the centripetal flow were deduced at several locations by measuring the drift of soap bubbles. Speeds as great as 2.3 $m\,s^{-1}$ were attributed to the heat-island effect. Chandler believed that the strongest circulations would be associated with summer or autumn nights having light winds, a stable atmosphere, and a well-developed heat island. However, daytime circulations may also exist. Findlay and Hirt (1969) discuss observations taken on a sunny, midwinter day with a 13-tower network of anemometers in Toronto, Canada. An inward flow was evident at the time of maximum heating.

This paper describes an investigation aimed at detecting the surface, heat-island circulation in and about St. Louis, Missouri using data from the 25 towers of the Regional Air Monitoring System (RAMS). In initial work with the RAMS data (Karl, 1976), objective analyses of summertime wind fields have revealed zones of horizontal convergence which might reflect urban modification of the flow, although these zones were not clearly related to the heat-island center. The St. Louis metropolitan area, inhabited by about 2.4 million people, is well suited for heat-island studies since it is a continental area and has only slight topographic relief. Meteorological data from RAMS include measurements of temperature, winds and atmospheric stability in both urban and rural locales. Large quantities of data are available on magnetic tape, allowing a statistical, rather than case-study approach in determining the thermally-induced circulation. Data from all of the year 1976 were scanned. This analysis is intended to define the magnitude of the circulation which may be expected for a given heat-island intensity and to assess the influences of atmospheric conditions and surface features on the magnitude or detectability of the circulation.

2. The RAMS Network and Data Analysis

Figure 1 depicts the urban areas in the vicinity of St. Louis as well as the RAMS monitoring sites, numbered 101 through 125. The rationale behind site selection and data requirements is reviewed by Pooler (1974). The RAMS was designed to provide information for the development, validation and improvement of urban-scale air quality models, and so supplies concentrations of pollutant gases as well as the meteorological data considered here.

There are seventeen 30-m towers and eight 10-m towers in RAMS, with wind sensors mounted on top of each. Wind speed is sensed by a three-cup anemometer,

Fig. 1. Urban areas in the St. Louis region, river systems, and locations of the RAMS sites. Solid dots indicate 30-m towers, while open circles indicate 10 m towers.

MRI Model 1022S, with a starting threshold of 0.22 m s^{-1} and an accuracy of 0.067 m s^{-1}. The wind direction sensor is MRI Model 1022D with a starting threshold of 0.3 m s^{-1}. Ambient temperature is measured at the 5-m level on each tower with the MRI Model 840-1 aspirated temperature sensor. The vertical temperature gradient, 5 to 30 m, is determined by the MRI Model 840–2 differential temperature sensor on all 30-m towers except those at Stations 103, 119, 120, 124, and 125. Voltage signals from each instrument are converted into one-minute average values and then recorded on magnetic tape. These data are screened for outliers by personnel of the Meteorology and Assessment Division of the U.S. Environmental Protection Agency, and the remaining measurements are used to form one-hour averages. The hourly averaged wind at each Station represents a vectorial average of the recorded one-minute values, and hourly averages are the fundamental data points used in this analysis.

A major difficulty in searching for centripetal flows is that few, if any, occurrences of calm winds would be found for one-hour periods. To allow for an adequate data sample, restriction on wind speeds must not exclude situations with

some large-scale flow, although it is obviously desirable that the flow remains weak. If a heat-island circulation does exist, it should be superimposed on the mean wind, and, therefore definable from the vector differences between the wind at each tower and the network resultant (vectorially-averaged) wind. Because sizable vertical wind gradients may exist, especially under stable atmospheric conditions, only the 30-m towers are used to compute the network wind. Not only are the taller towers more numerous, but they are concentrated about central St. Louis where the convergence zone may be expected. The 30-m towers are numbered 101–107, 109, 111–113, 119–120, and 122–125, while the 10-m towers are numbered 108, 110, 114–118, and 121 (see Figure 1). All towers are used to compute the heat-island isotherms.

A scan was made of the data from each hour of 1976. For the data from a particular hour to be included in the analysis, the network, vectorially-averaged wind speed was required to be less than $1.5\ m\ s^{-1}$, and the network, scalar-averaged wind speed was required to be less than $3.0\ m\ s^{-1}$. This selection scheme assured low speed flows while excluding certain rare cases which may be associated with frontal passages. To assure that adequate data were available, fourteen of the seventeen 30-m towers had to report a valid wind speed and direction, or the hour was not included in the analysis.

In addition to wind measurements, information on the heat-island intensity and atmospheric stability was required to characterize the situations. Urban and rural temperatures (T) were determined as the mean of observations at Stations 101–107 and 114–125, respectively. Urban and rural vertical temperature differences (DT) were calculated as the mean of measurements at Stations 101, 102, 104–107 and Stations 109, 122, 123, respectively. More than one half of the Stations in each group of T and DT were required to report valid measurements, or no data from the hour were included in the analysis.

Once data of a particular hour had cleared the tests outlined above, they were classified according to heat-island intensity, defined as the difference between mean urban and rural temperatures. The low and high heat-island intensities (LHI and HHI) were defined as less than or greater than 1 °C. This classification of the data was originally designed to investigate the response of the circulation to changes in the forcing but, as will be seen shortly, also leads to a rather dramatic illustration of a confounding effect due to atmospheric stability. Considering all of 1976, data from 230 hours were admitted to the LHI class, while data from 400 hours were admitted to the HHI class.

Suppose a heat-island class (LHI or HHI) contains the data for n hours chosen from throughout the year by the previously described selection process. For the jth Station at the ith hour, let U_{ij} and V_{ij} be the wind vector components measured positive for westerly and southerly flows, respectively. Furthermore, let U_i and V_i be the corresponding components of the network, resultant wind (the means of U_{ij} and V_{ij} over j based on data from the 30-m towers). The differences of the local

wind from the network wind are expressed as

$$u_{ij} = U_{ij} - U_i$$

and

$$v_{ij} = V_{ij} - V_i .$$

The mean difference in the U component over all hours in the data class is

$$\bar{u}_j = (1/n) \sum_{i=1}^{n} u_{ij} ,$$

with standard deviation of the mean difference being

$$\text{s.d. } \bar{u}_j = (1/n)\left(\sum_{i=1}^{n} u_{ij}^2 - n\bar{u}_j^2 \right)^{0.5}$$

$\bar{v}_j$ and s.d. $\bar{v}_j$ are computed in analogous fashion. The pattern of mean difference vectors, or net circulation, may reveal the heat-island-generated, centripetal flow under proper conditions.

3. Results

Figures 2 and 3 show the mean-heat island isotherms as well as mean difference vectors for the 30-m RAMS Stations from data of the LHI and HHI classes, respectively. Table I gives corresponding standard deviations of the mean difference components for judging the significance of the indicated net circulations. To avoid cluttering the Figures, only a few Stations have been numbered; others can be easily identified with the aid of Figure 1.

Two major results are immediately apparent from these Figures. First, a centripetal circulation is indeed detectable, strikingly so at the central Stations 101, 105, 106 and 107. Second, the convergence is stronger for the LHI class than for the HHI class. Whereas the first result is certainly gratifying, the second is rather startling when considering the traditional views expressed by Chandler (1965). In looking at Figures 2 and 3, it is important to notice that the LHI isotherms are at 0.25-deg intervals while the HHI isotherms are at 1-deg intervals. The peak of the mean heat island under LHI conditions is about 0.7 °C while that for HHI conditions is about 3.3 °C. Yet, the inward flow is perhaps twice as strong for the LHI data class. To understand this result, attention is now turned to the characteristics of the data within each heat-island class.

Histograms of data attributes, Figure 4, show that the classification by heat-island intensity also divides the data quite distinctly according to time of day and atmospheric stability. DT of about −0.25 °C would indicate a zero gradient of potential temperature; therefore, the histogram bar for −0.4 to 0.0 °C is labeled 'near adiabatic'. The LHI data have been overwhelmingly selected from daytime

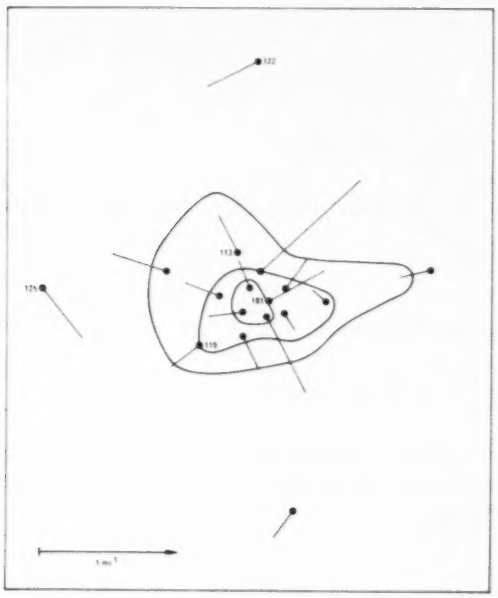

Fig. 2. Mean isotherms and difference wind vectors for the LHI data class. Isotherm intervals are 0.25 °C. Network, resultant speed is less than 1.5 m s^{-1}.

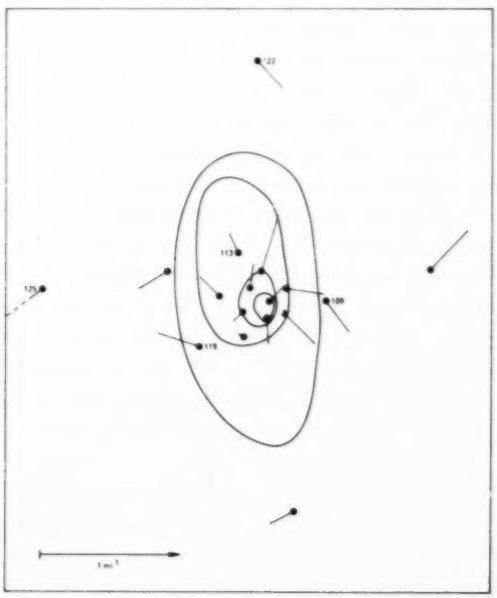

Fig. 3. Mean isotherms and difference wind vectors for the HHI data class. Isotherm intervals are 1.0 °C. Network, resultant speed is less than 1.5 m s^{-1}.

TABLE I

Standard deviations of the mean difference components as a percent of the difference vector magnitude, $m_i = (\bar{u}_i^2 + \bar{v}_i^2)^{0.5}$

Station	(100×s.d. $\bar{u}_i/m_i$, 100×s.d. $\bar{v}_i/m_i$)	
	LHI	HHI
101	10,9	15,14
102	6,5	7,7
103	18,18	11,11
104	33,38	10,11
105	7,9	12,15
106	14,16	21,[illegible]
107	16,16	11,[illegible]
109	34,43	12,13
111	17,27	74,109
112	15,12	11,11
113	13,15	35,22
119	16,17	9,9
120	12,12	20,17
122	14,18	21,20
123	27,27	11,12
124	30,34	29,35
125	14,18	13,14

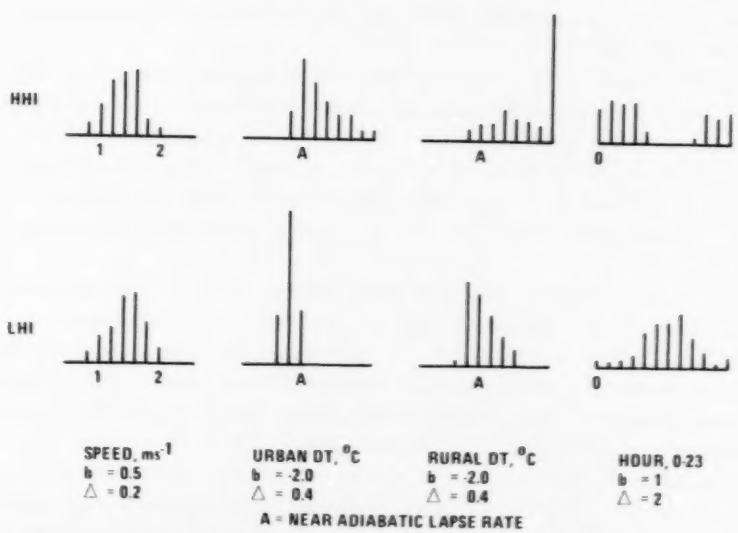

Fig. 4. Histograms of data characteristics within the classes of heat-island intensity. Each histogram divides the data into twelve attribute segments and gives the percent of data in each segment. The first segment refers to data with attribute less than or equal to b, the last segment refers to data with attribute greater than $b + 10\Delta$, and the intervening scale is divided into equal segments of size Δ.

hours with unstable conditions in both the urban and rural locales, and greater instability in the city. The HHI data, on the other hand, are strongly associated with nighttime hours exhibiting extreme stability in the countryside and a tendency towards neutrality in the city. The attendant stability conditions in the two heat-island classes are likely responsible for the results which, when considering the forcing involved, seem contradictory. The speed histograms in Figure 4 refer to the network, scalar-averaged speed. It is seen that the speeds recorded by the Stations are similar under either heat-island condition.

For an inward flow of air to exist, a mean vertical motion must be present over the central city. This relatively slow, mean updraft is likely composed of, and triggered by, more vigorous, intermittent and discontiguous, turbulent motions, with air parcels rising freely to considerable heights. The unstable conditions comcomitant with the LHI class are conducive to strong vertical motions. On the other hand, the neutral conditions associated with the HHI class do not support sustained vertical motions. For the HHI class, the existence of near-neutral conditions in the city indicates that stable, rural air drifting into the city has been mixed by the available thermal energy, but only in a relatively shallow layer. The mixing depth is symptomatic of the strength of vertical motions, and, for HHI conditions, the mixing depth may be several hundred meters over the city while very shallow or nonexistent in the adjacent countryside. However, for the convective conditions of the LHI class, the mixing depth may typically be one to two kilometers (Endlich *et al.*, 1978). Simply stated, the atmosphere is much more able to respond to the available forcing under unstable, convective conditons such as those associated with data in the LHI class.

The surface convergence may be estimated by looking at Stations 101, 105, 106 and 107, which form the conspicuous quadrangle in central St. Louis. Looking first at the LHI results (Figure 2), Stations 101 and 106, separated by 6.6 km, show approximately opposing flows of 0.45 and 0.25 $m\,s^{-1}$. Stations 105 and 107, separated by 7.0 km show opposing flows of about 0.60 and 0.20 $m\,s^{-1}$. The computed convergence is then $2.2\times10^{-4}\,s^{-1}$. A similar calculation for HHI (Figure 3) gives $9.1\times10^{-5}\,s^{-1}$.

Figures 2 and 3 indicate that the outer Stations, 122–125, do not sense the heat-island circulation. Station 102 shows a relatively large inflow speed for both data classes. The flow impinging on 102 transverses a long fetch over the Mississippi River, so this may also reflect a component of 'river breeze'. Table I indicates that the mean flow at most Stations is well-defined and no major differences exist between the heat island data classes in this respect.

The typical heat island flow detected by this method has speed of order 0.3 $m\,s^{-1}$. As seen from the histograms for speed in Figure 4, the expected wind speed at a Station has a median of about 1.4–1.5 $m\,s^{-1}$ in both heat-island classes; therefore, the mean heat-island circulation has a magnitude much less than the typical speeds being recorded. It is difficult to see how the centripetal circulation could be reliably discerned by examining the absolute winds, components U_{ij} and V_{ij}, rather than the

difference winds, components u_{ij} and v_{ij}. Also, it should be understood that the sample standard deviation of a component is divided by the square root of the sample size to estimate the standard deviation of the mean component. The values in Table I should be multiplied by 15 or 20 to arrive at the standard deviations of the components in the samples. Therefore, even using the net circulation, the chance of discovering such a definitive centripetal flow for a randomly selected hour appears to be slim indeed.

To examine individual situations representative of the LHI and HHI classes, difference vectors were plotted separately for hours with computed heat-island intensities of 0.5–0.7 °C (34 hours) and 2.4–2.6 °C (43 hours), and Figures 5 and 6 display sets of six plots chosen from these samples. One of the plots in each Figure was chosen (subjectively) as the best example of a centripetal flow found in the corresponding sample, while the other five may be regarded as fairly representative of the remaining hours. The outer Stations 122–125 do not appear in these plots, and only a single isotherm is drawn to indicate the location of the temperature peak. The peak tends to show some movement in response to wind direction. Generally, hour-by-hour isotherm patterns lack the integrity manifested by the mean patterns in Figures 2 and 3, and some evidence of double peaks is seen.

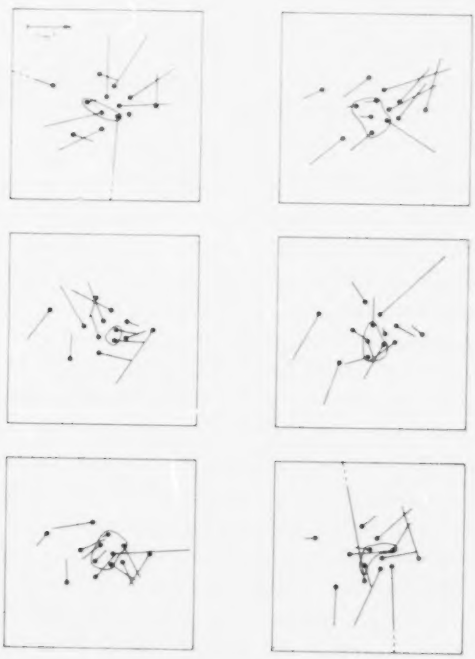

Fig. 5. Hourly plots of difference wind vectors obtained from a sample of the LHI data class. A single isotherm indicates the heat island peak. The best example is given in the upper left.

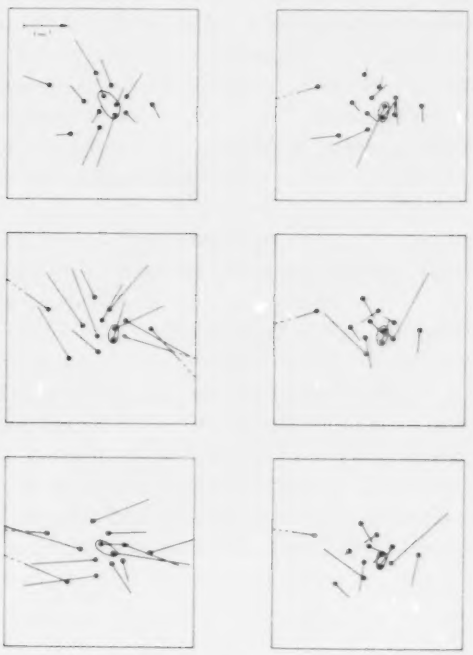

Fig. 6. Hourly plots of difference wind vectors obtained from a sample of the HHI data class. A single isotherm indicates the heat island peak. The best example is given in the upper left.

Allowing that recognition of heat-island influence on the wind field is a subjective matter, it appears that inward flows are perceptible in a majority of the plots, and, as a general proposition, the flows are better defined for the LHI sample than for the HHI sample. In either case, the more well-defined flows are correlated with low network speeds and more negative (less positive) urban DT's. Although a centripetal pattern is usually recognizable, the recorded winds at specific sites often bear little or no relation to the location of the temperature peak, and this is the source of the variability in the data as previously discussed. For hours when the network speed exceeds 1 m s^{-1}, there are clear examples where the centripetal flow is evident from the difference winds but not the absolute winds. Inflow speeds as high as 2–3 m s^{-1}, due solely to the heat island (Gold, 1956; Chandler, 1965), are not typical. The best example from the LHI sample, Figure 5(a), has a temperature peak of 1 °C, a network speed of 0.3 m s^{-1}, and an urban DT of −0.5 °C; the best example from the HHI sample, Figure 6(a), has a temperature peak of 4 °C, a network speed of 0.7 m s^{-1}, and an urban DT of 0.3 °C. Estimated horizontal convergences for the best examples are perhaps four times as great as for the mean patterns. These hour-by-hour plots support the conclusion that the forcing, if measured by the urban-rural temperature difference, is of less importance than the

attendant stability in determining the strength and definition of the heat-island circulation.

4. Results for Higher Speed Flows

A question naturally arises as to how strong the large-scale flow needs to be before it is impossible to detect a heat-island circulation. As the speed increases, terrain and roughness features will, it is suspected, play a larger role. Their perturbations are likely to be proportional to the strength of the large-scale flow and will eventually obscure the centripetal circulation.

To investigate this question, four additional data classes were formed. Data selection followed the same scheme as used before except that the resultant speed for the network was required to be 1.5–3.0 m s^{-1}. Since flows of this strength tended to have well-defined directions, the data were divided according to 45-deg direction sectors centered on North (N) and South (S), as well as heat-island intensity. The four classes thus formed were denoted N–LHI, N–HHI, S–LHI and S–HHI and contained, respectively, 90, 148, 158, and 327 hours of data. Splitting the data by heat-island intensity effected a partition according to stability and time of day similar to that seen already for the lower speed winds (Figure 4).

For these higher speed winds, a centripetal flow can no longer be detected, nor are the magnitudes of the difference vectors appreciably disparate among the heat-island classes. However, the influence of the Mississippi River Valley is evident as illustrated in Figures 7 and 8 which present net circulations for the N–HHI and S–HHI classes. Speeds recorded along the river by Stations 101, 103, 104, and 105 are higher in the direction of the network wind than speeds recorded at Stations away from the river. To some degree, the net flow appears to be a counterclockwise circulation for South winds and a clockwise circulation for North winds. North-South and East–West topographic cross-sections are presented in Figure 9. The higher speeds along the river likely result from reduced drag on the smooth water surface in conjunction with channelling along the valley. There is no indication in the present study that Coriolis force has a detectable influence on the net circulation, although Figure 7 illustrates the danger of misinterpreting topographic effects and concluding the presence of a cyclonic flow about a heat-island center.

Just as a correction was made to compensate for the influence of the synoptic pressure gradient, it seemed it might be possible to remove the topographic and roughness effects seen in Figures 7 and 8. To this end, the South-wind samples were restricted so that each South-wind class contained the same number of hours as its respective North-wind class. The LHI and HHI classes from each direction were then combined. In this way, the influence of the river on the flow might be counterbalanced. However, a clear centripetal pattern did not emerge from this exercise, and the result casts doubt on the notion that centripetal flows can be detected for conditions other than those approaching calm.

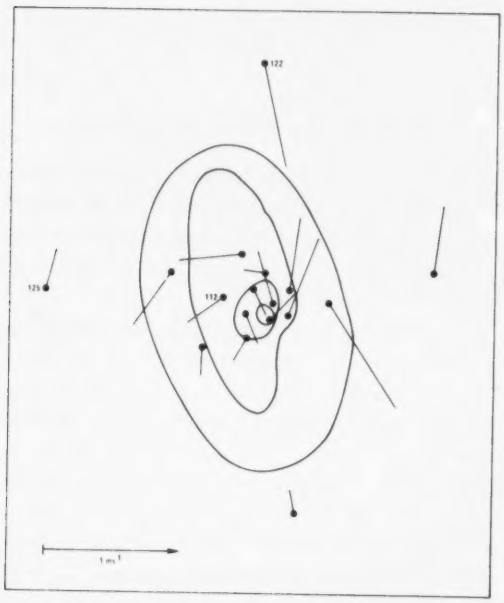

Fig. 7. Mean isotherms and difference wind vectors for the N–HHI data class. Isotherm intervals are 1.0 °C. Network, resultant speed is 1.5–3.0 m s^{-1}.

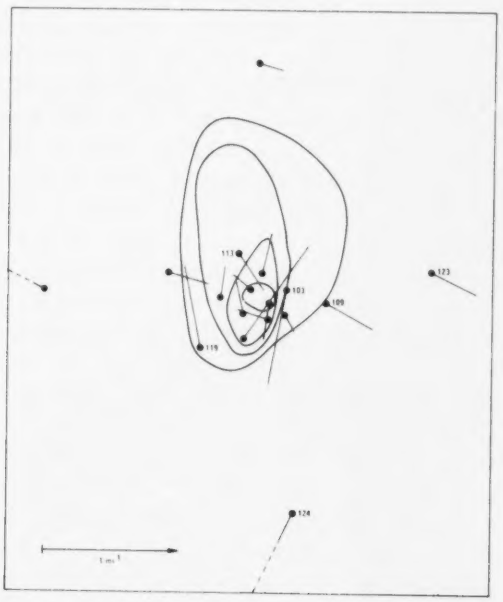

Fig. 8. Mean isotherms and difference wind vectors for the S–HHI data class. Isotherm intervals are 1.0 °C. Network, resultant speed is 1.5–3.0 m s^{-1}.

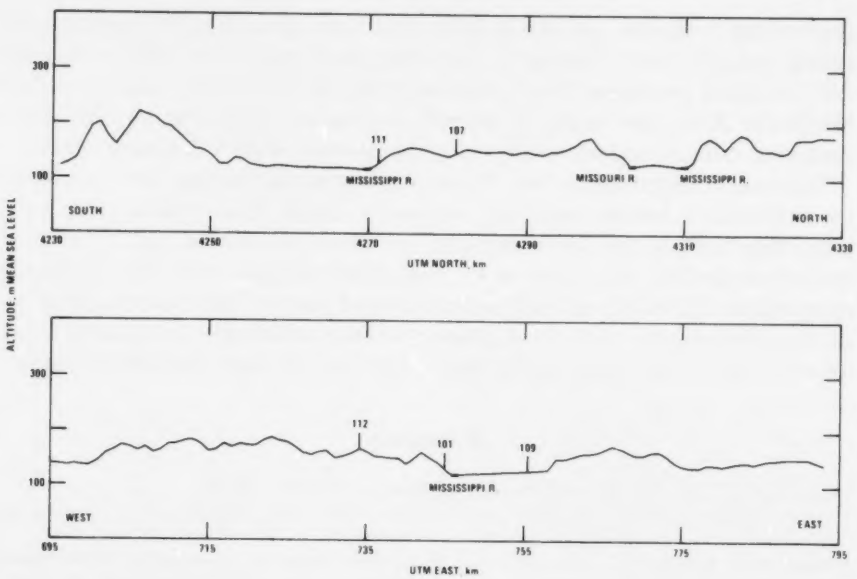

Fig. 9. East–West and North–South topographic cross-sections passing approximately through Stations 101 and 107, respectively. Selected 30-m towers are drawn to scale.

5. Concluding Remarks

Using data gathered when the resultant speed for the network was less than $1.5\ m\ s^{-1}$, it was demonstrated that centripetal flows are detectable as the net circulation after removal of the large-scale wind. For samples containing several hundred hours of data, the mean horizontal convergence was of the order $10^{-4}\ s^{-1}$.

Assuming the existence of a surface heat island, attendant conditions of atmospheric stability play a decisive role in determining the strength of centripetal flows which are detectable from tower-measured winds. Strongly stable conditions in rural areas, conditions associated with nocturnal hours and the most intense heat islands, are not conducive to an inward flow since vertical motions over the city are suppressed. Conditions of convective instability, conditions associated with daytime hours and weak heat islands, are helpful in producing such a circulation since vertical motions may be initiated with a relatively small input of thermal energy from the urban surface. This qualitative argument seems reasonable in view of the empirical evidence. It is an observation of some importance, and there is an obvious need for numerical modeling to define the precise relation between heat-island intensity, stability and strength of the convergence.

The ability to detect a centripetal flow diminishes rapidly with increasing speed. For network speeds of $1.5–3.0\ m\ s^{-1}$ from the North or South, the net circulation shows influence of the Mississippi River but not the heat island. Attempts to

remove this roughness and topographic effect were unsuccessful. Therefore, the surface-generated perturbations in even these weak flows are capable of masking the heat-island circulation. Generalization of this result may be unwarranted. The Mississippi River can hardly be termed a minor anomaly, but all cities have distinctive surface features and St. Louis has relatively slight topographic relief.

This study is statistical in nature. Some characteristics of the data were examined, but individual situations were not analyzed in detail. Case studies may reveal interesting facets of the development of heat-island circulations, but, considering the present findings, the existence of a heat island and light winds does not justify expectation of a sharply-defined centripetal wind pattern. This analysis should be useful in defining the mean, heat-island circulation which may be expected under different conditions of wind speed, heat-island intensity and atmospheric stability.

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